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Title: Double Beta Decay: Is the Neutrino Mass within Reach?

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Intended for: Colloquium at the Univ. Tenn.

Los Alamos

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Double Beta Decay: is the neutrino mass within reach

- Neutrinos
- Science of ββ
- MAJORANA Demonstrator

Why Neutrinos?

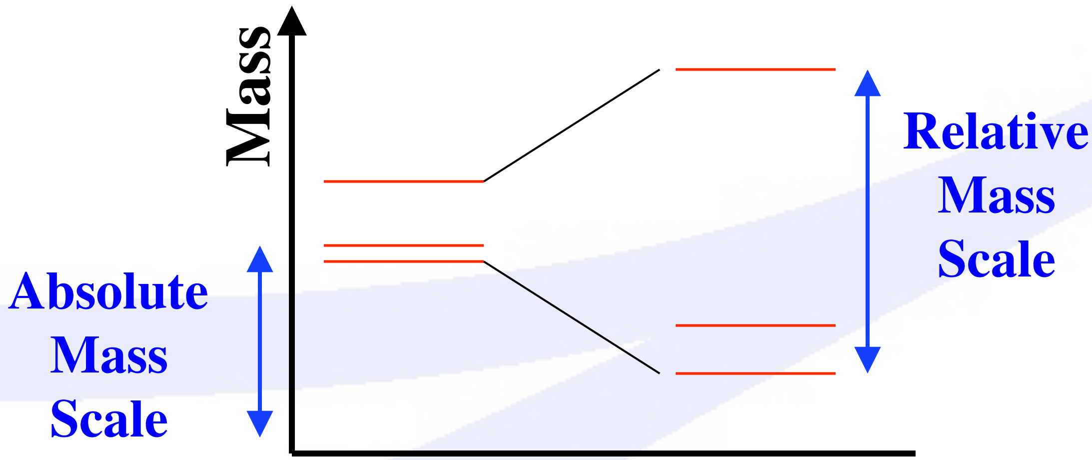
ν properties are critical input to many physics questions

- **Particle/Nuclear Physics**
  - **Fundamental questions about standard model**
  - **Fundamental issues regarding interactions**
- **Cosmology**
  - **Large scale structure**
  - **Leptogenesis and matter-antimatter asymmetry**
- **Astrophysics**
  - **Supernova explosions**
  - **Solar burning**

Why are neutrinos unusual?

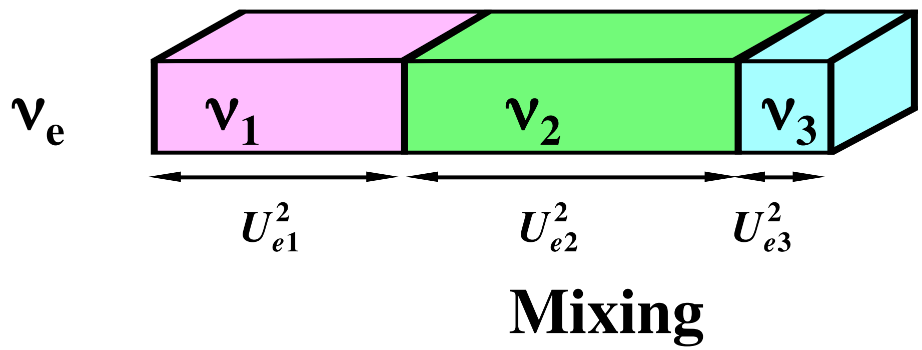
- **Because the neutrino only interacts weakly, it is a very difficult particle to study. We don't know much about it.**
- **Neutrinos might be the ultimate neutral particle**
  - **They would not be distinct from their antiparticles.**
  - **If so they would be Majorana particles**
- **They might also be Dirac particles**
  - **Like the charged quarks and leptons**
- **The difference between these two possibilities greatly influences how the neutrino is incorporated into the Standard Model**

Neutrinos: What do we want to know?



Dirac or Majorana

$$\begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \\ \bar{\nu}_{\downarrow} \\ \bar{\nu}_{\uparrow} \end{pmatrix} \text{ or } \begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \end{pmatrix}$$



Neutrino Masses: What do we know?

- **The results of oscillation experiments indicate ν do have mass!, set the relative mass scale, and a minimum for the absolute scale.**
- **β decay experiments set a maximum for the absolute mass scale.**

50 meV $< m_\nu <$ 2200 meV

We also know ν mix.

The weak interaction produces ν_e, ν_μ, ν_τ.

These are not pure mass states but a linear combination of mass states.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

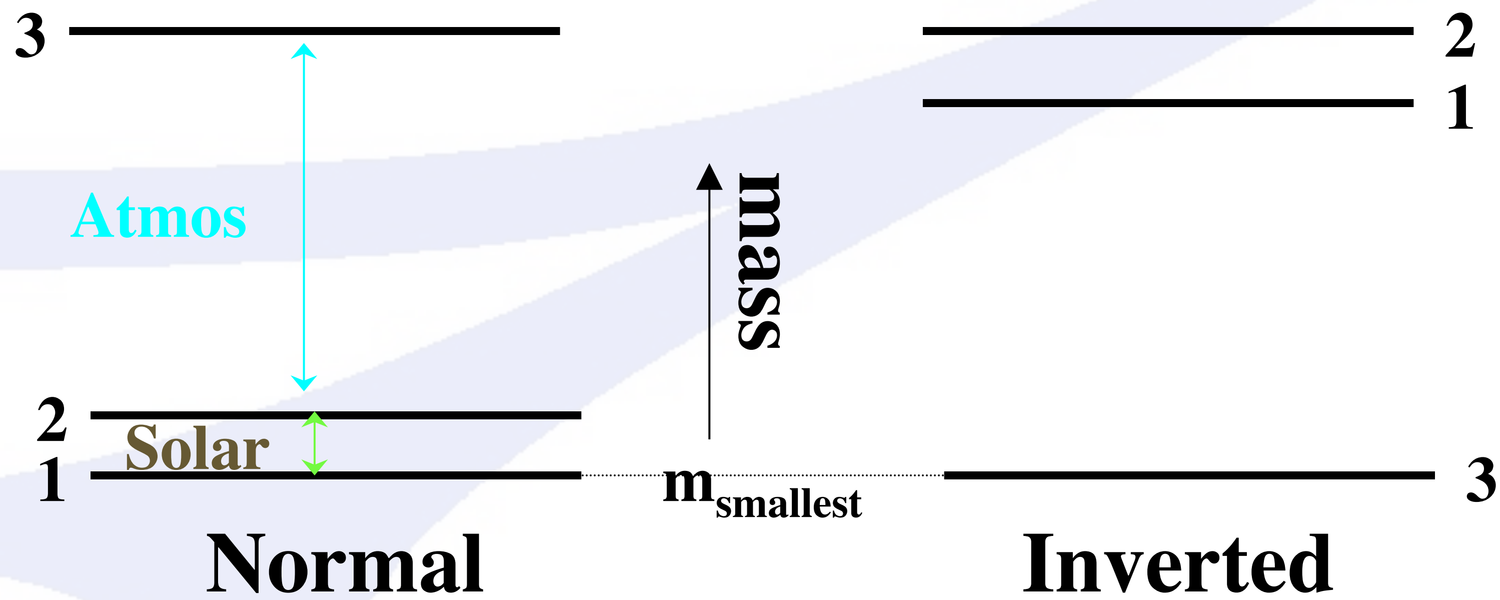
Oscillation experiments indicate that ν mix and constrain $U_{\alpha i}$.

The Standard Model Particles

Quarks	u up	c charm	t top	γ gamma	Force Carriers
	d down	s strange	b bottom	g gluon	
Leptons	ν_3	ν_1	ν_2	W W boson	
	e electron	μ muon	τ tau	Z Z boson	

The Neutrinos

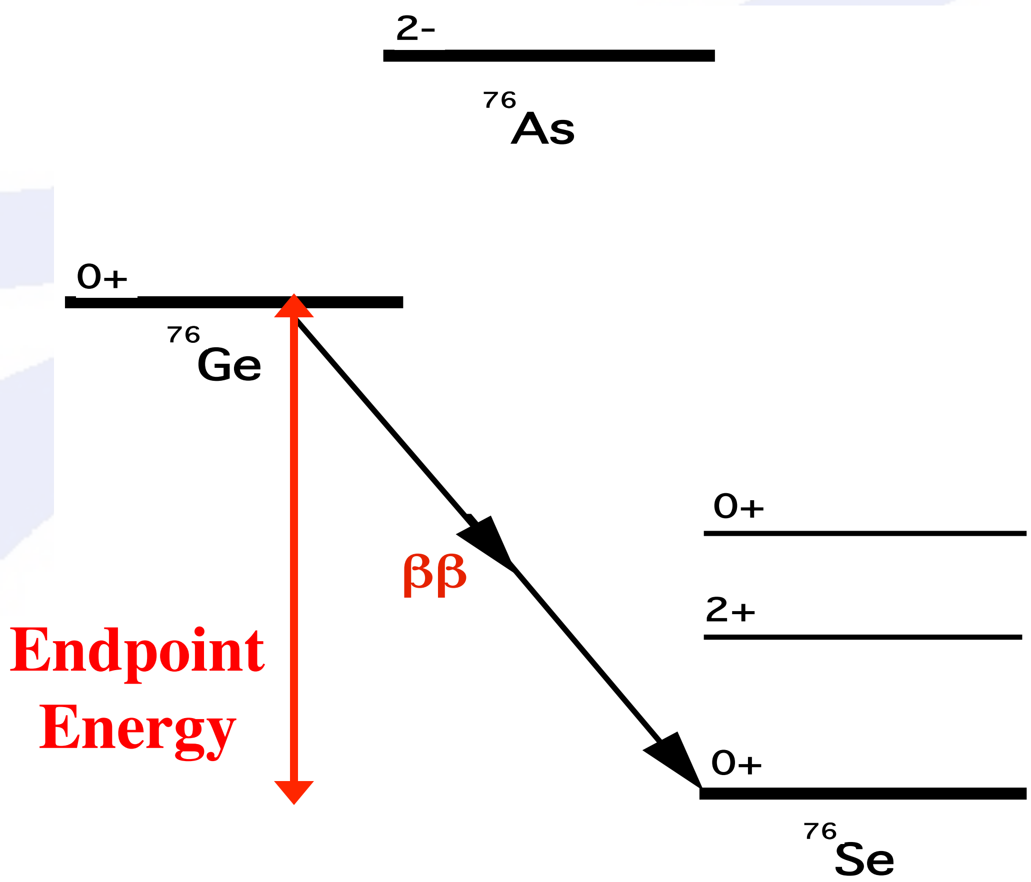
Oscillations and Hierarchy Possibilities



ν_e is composed of a large fraction of ν_1.

Example ββ Decay Scheme

In many even-even nuclei, β decay is energetically forbidden. This leaves ββ as the allowed decay mode.



What is ββ?

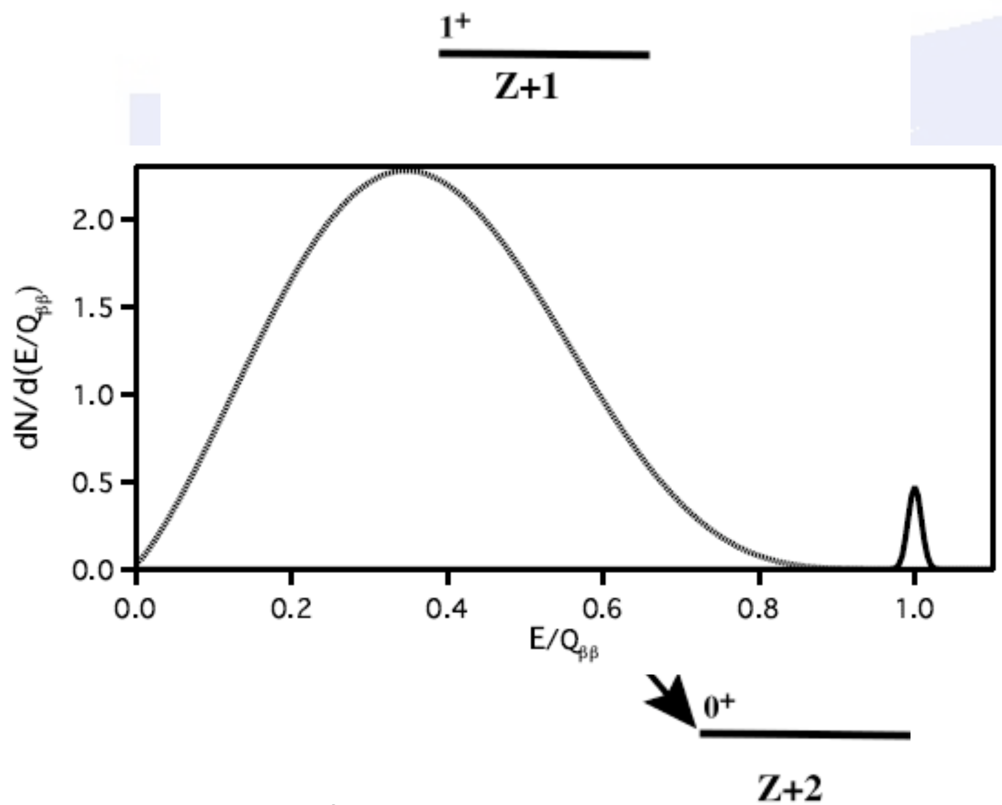


Fig. from arXiv:0708.1033

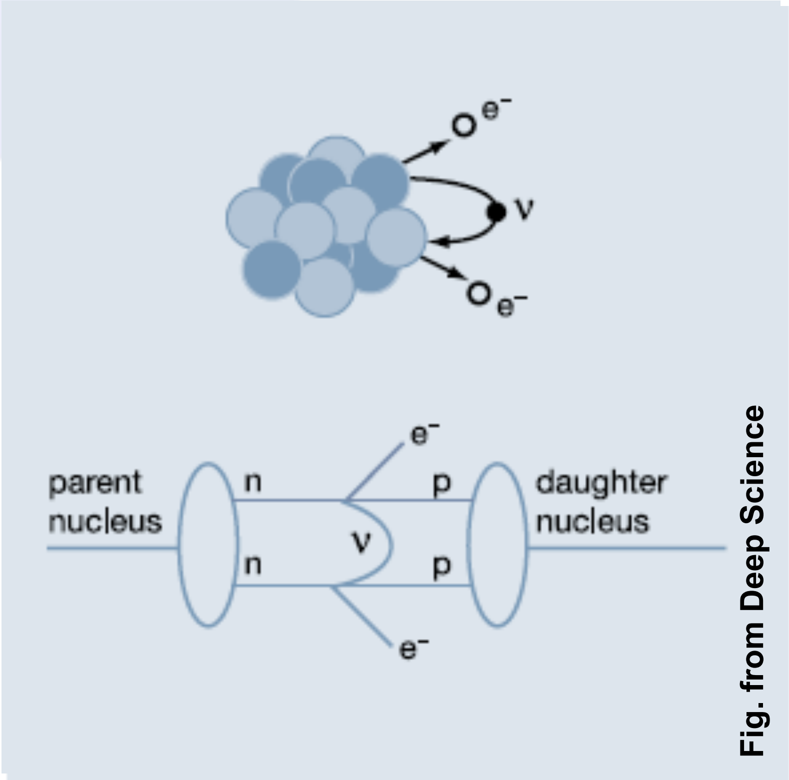


Fig. from Deep Science

$\beta\beta$ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\boxed{\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2}$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.

What about mixing, m_ν & $\beta\beta(0\nu)$?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i$$

virtual ν exchange

$\varepsilon = \pm 1$, CP cons.

Compare to β decay result:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

real ν emission

Compare to cosmology:

$$\Sigma = \sum m_i$$

What can be learned from Oscillations & ββ?

- **From oscillations, we have:**
  - **Information on U_{ei}**
  - **Information on δm^2**

- **With $<m_{\beta\beta}>$ constraints, we can constrain m_1: (2 flavor example)**

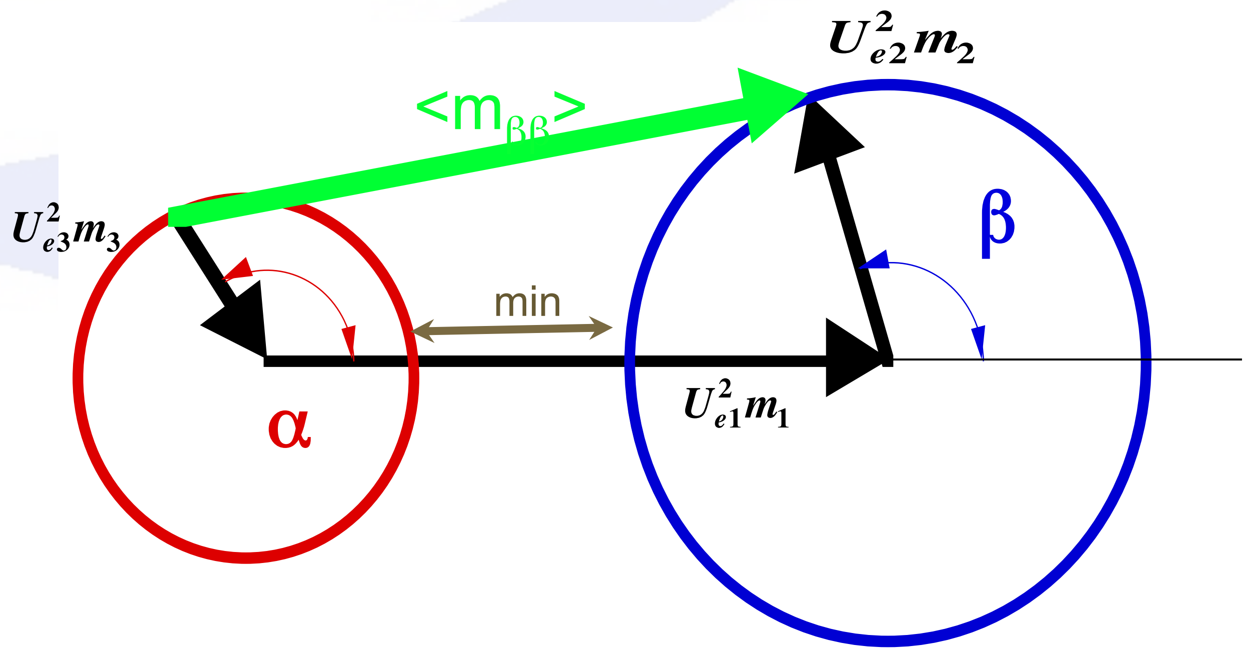
$$\langle m_{\beta\beta} \rangle = U_{e1}^2 m_1 + \varepsilon_{21} U_{e2}^2 \sqrt{m_1^2 + \delta m_{21}^2}$$

Min. $\langle m_{\beta\beta} \rangle$ as a vector sum. General Case

$$\boxed{\langle m_{\beta\beta} \rangle = \left\| U_{e1} \right|^2 m_1 + e^{i\beta} \left| U_{e2} \right|^2 m_2 + e^{i\alpha} \left| U_{e3} \right|^2 m_3 \right\|}$$

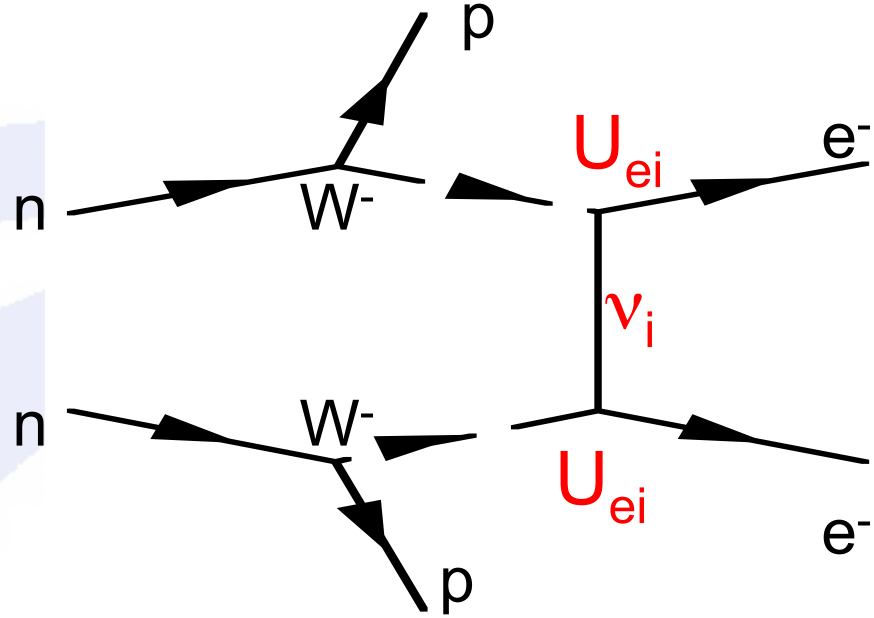
$\langle m_{\beta\beta} \rangle$ is the modulus of the resultant.

In this example, $\langle m_{\beta\beta} \rangle$ has a min. It cannot be 0.



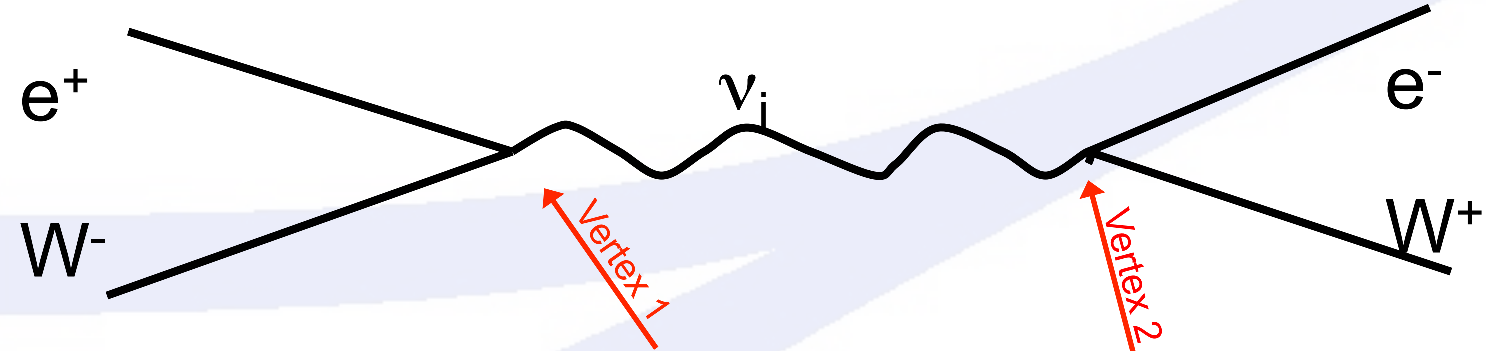
Why does the CP parity appear in $\langle m_{\beta\beta} \rangle$?

$$A_{0\nu} \sim \Sigma_i$$



- **Look at the critical part of this diagram.**

The crossed channel.



$$A \propto \sum_i U_{ei}^2 \langle e^+W^- | H_{SM} | \nu_i \rangle \langle \nu_i | H_{SM} | e^-W^+ \rangle$$

The 1st vertex creates the CP partner of the particle needed by the 2nd vertex.

$$\text{But } CP|\nu_i\rangle = \varepsilon_i |\nu_i\rangle$$

Upon substitution, the factor ε_i appears.

The importance of Majorana neutrinos and Lepton number conservation violation

Dirac Picture

$$\begin{pmatrix} \nu_L \\ \nu_R \\ \bar{\nu}_R \\ \bar{\nu}_L \end{pmatrix}$$

A Dirac mass mixes these Helicity-related states

Majorana Picture

$$\begin{pmatrix} \nu_L \\ \bar{\nu}_R \end{pmatrix} \quad \begin{pmatrix} \bar{\nu}_L \\ \nu_R \end{pmatrix}$$

A Majorana mass mixes these Helicity-related states

Majorana neutrinos lead to Lepton number violation

All ββ transitions

Require Majorana mass to mix helicity states for non-zero rate

Standard Model
LHC vertices
(Similar for 2 RHC vertices)

Majorana-style helicity flip

$$n \Rightarrow p + e_L^- + \bar{\nu}_R \qquad \nu_L + n \Rightarrow p + e_L^-$$

LHC at 1st vertex
RHC at 2nd vertex

Again requires
Majorana mass

$\bar{\nu}_L$

Dirac-style flip **Majorana-style flip**

$$n \Rightarrow p + e_L^- + \bar{\nu}_R \qquad \nu_R + n \Rightarrow p + e_R^-$$

Majorana-style flip **Dirac-style flip**

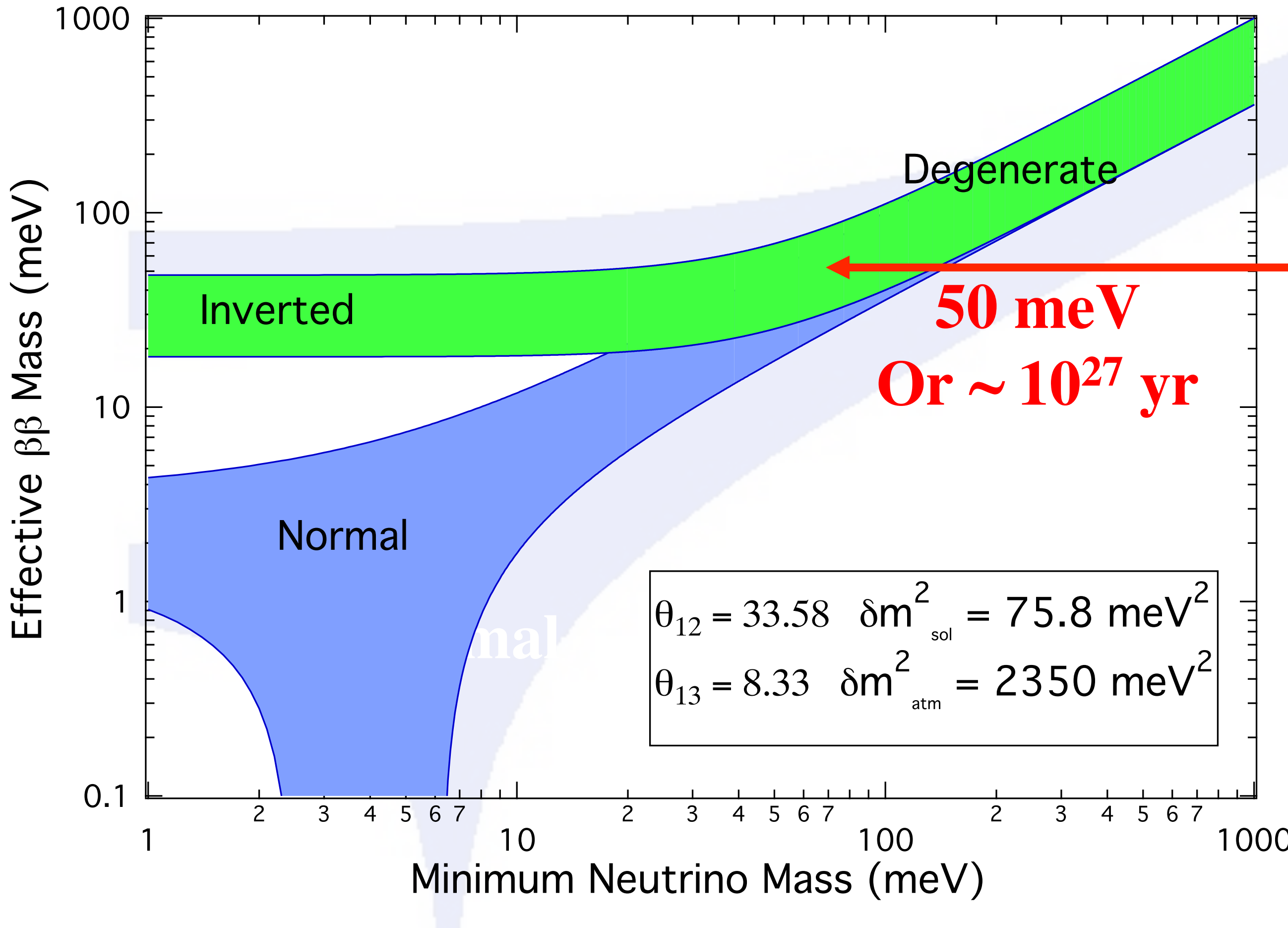
ν_L

ββ and the neutrino

- ββ(0ν) decay rate proportional to neutrino mass
  - Most sensitive technique (if Majorana particle)
- Decay can only occur if Lepton number conservation is violated
  - Leptogenesis?
- Decay can only occur if neutrinos are massive Majorana particles
  - Critical for understanding incorporation of mass into standard model
  - ββ is only practical experimental technique to answer this question
- Fundamental nuclear/particle physics process

ββ Sensitivity

(mixing parameters from arXiv:1106.6028)



Even a null result will constrain the possible mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~20 meV would exclude Majorana neutrinos in an inverted hierarchy.

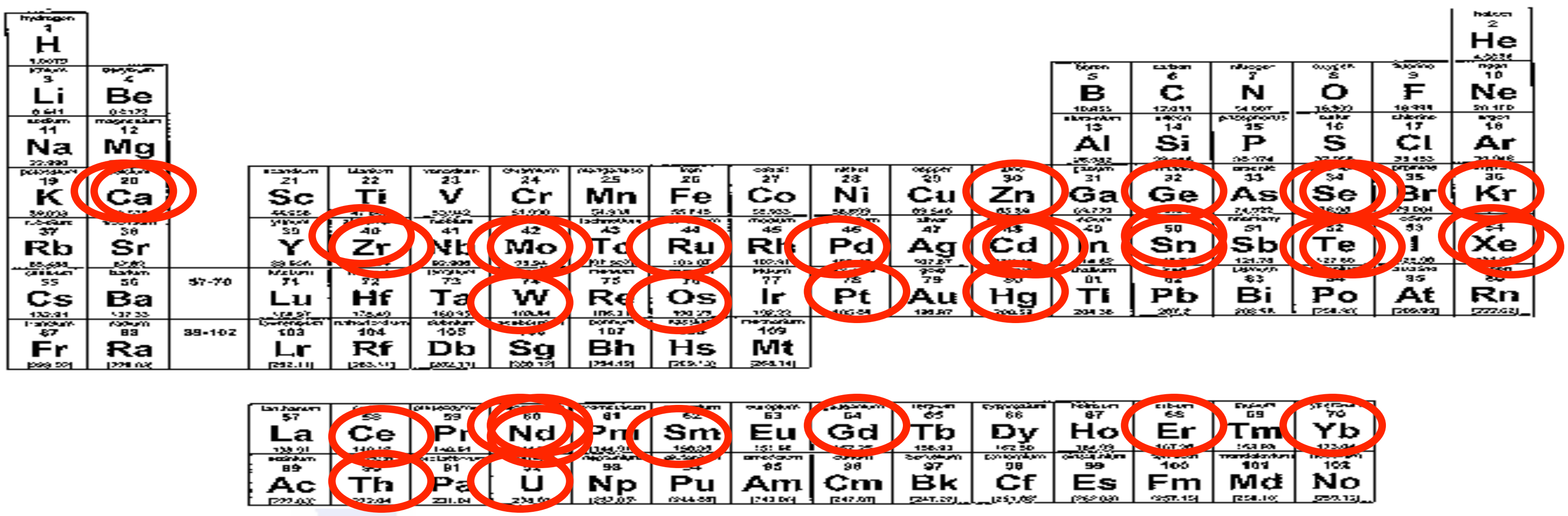
$\beta\beta$ History

- $\beta\beta(2\nu)$ **rate first calculated by Maria Goeppert-Mayer in 1935.**
- **First observed directly in 1987.**
- **Why so long? Background**
  - $\tau_{1/2}$**(U, Th) ~** $T_{universe}$
  - $\tau_{1/2}(\beta\beta(2\nu))$ **~** 10^{10} $T_{universe}$

- **But next we want to look for a process with:**
  - $\tau_{1/2}(\beta\beta(0\nu))$ **~** 10^{17} $T_{universe}$

ββ Candidates

There are a lot of them!

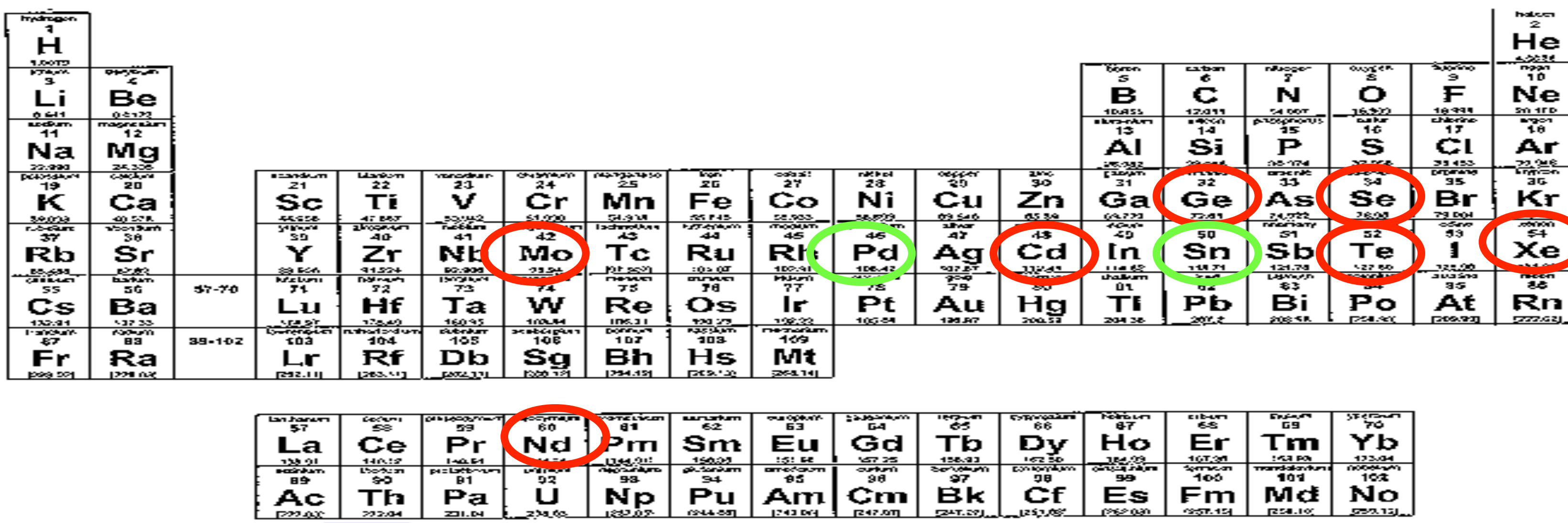


How to choose a $\beta\beta$ isotope?

- **Detector technology exists**
- **High isotopic abundance or an enriched source exists.**
- **High energy = fast rate, above background**

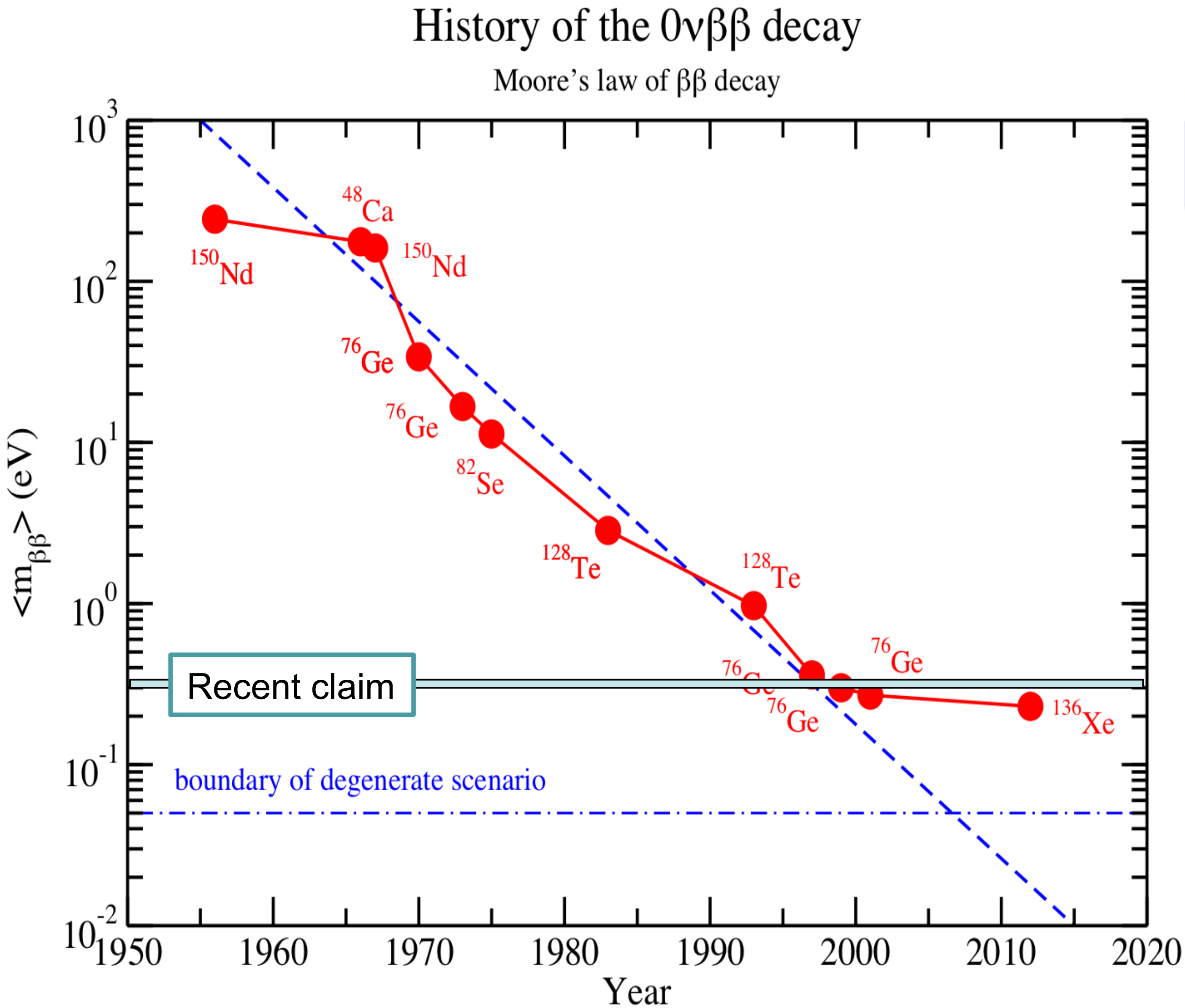
ββ Candidates

Abundance > 5%,Trans. Energy > 2 MeV



Frequently studied isotope.

ββ trends (updated Elliott/Vogel plot by Vogel)



Historically, there are > 100 experimental limits on $T_{1/2}$ of the 0νββ decay.
Here are the records expressed as limits on <$m_{\beta\beta}$> using one set of nuclear matrix elements (RQRPA of Simkovic et al. 2009.)
Note the approximate linear slope vs time on such semilog plot.
However, during the last decade the complexity and cost of such experiments increased dramatically.
The constant slope is no longer maintained.

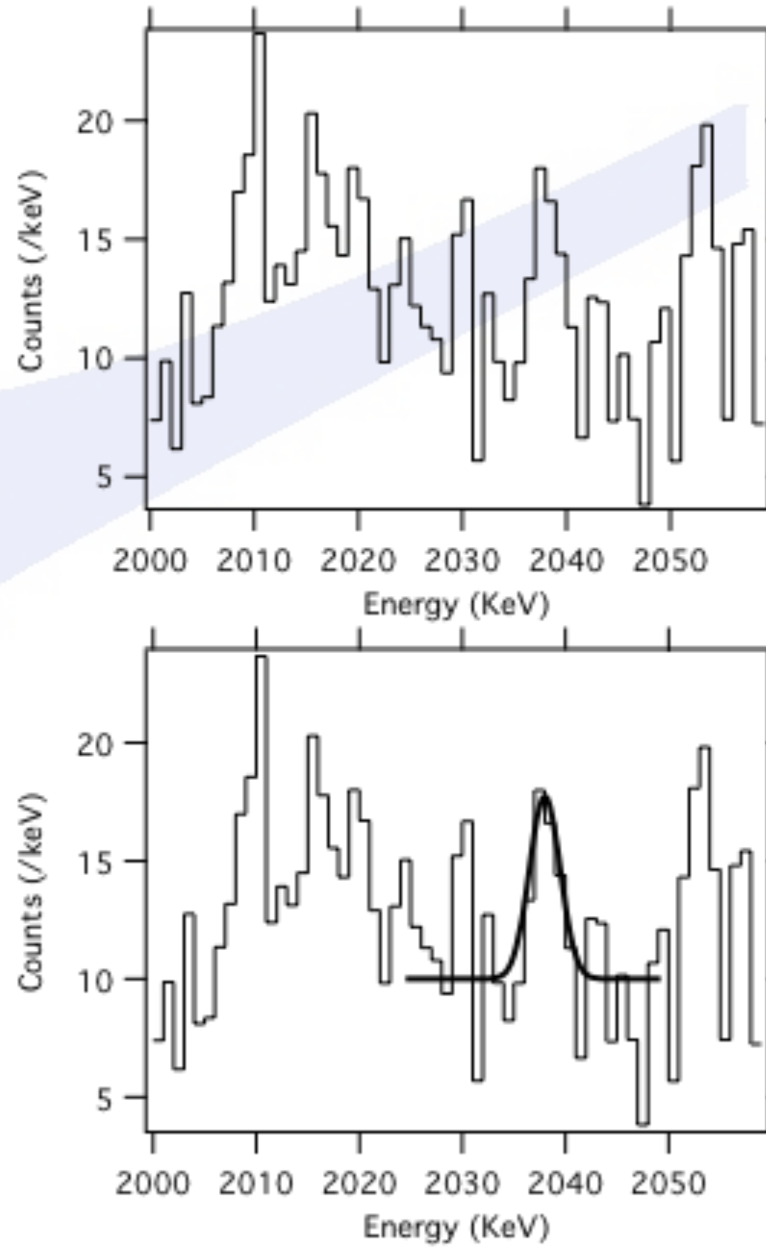
A Claim

has become a litmus test for future efforts

ββ is the search for a *very* rare peak on a continuum of background.

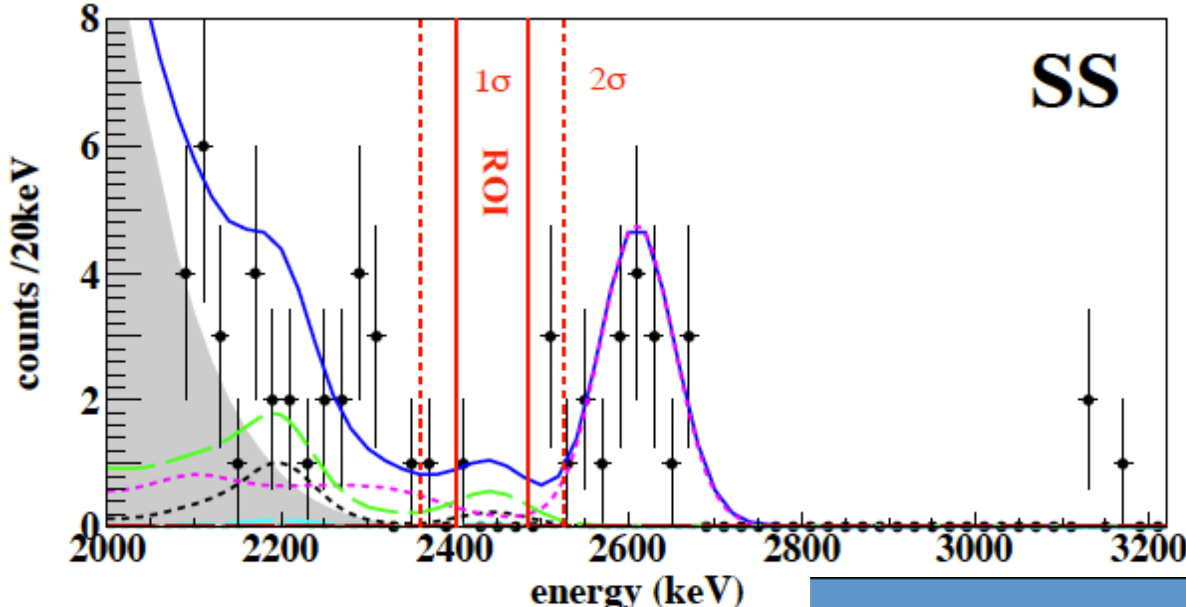
~70 kg-years of data
13 years

The "feature" at 2039 keV is arguably present.



NIM A522, 371 (2004)

EXO result



Joint analysis with KamLAND-Zen gives 3.4×10^{25} y, 120-250 meV
arXiv:1211.3863

$T_{0\nu} > 1.6 \times 10^{25}$ y
$m_{\beta\beta} < 140$-380 meV
120.7 days
79.4 kg ^{136}Xe
PRL 109, 032505

	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5\cdot10^{-3} \pm 0.1$		$1.4\cdot10^{-3} \pm 0.1$	

Future Data Requirements

Why wasn't the claim sufficient to avoid controversy?

- **Low statistics of claimed signal - hard to repeat measurement**
- **Background model uncertainty**
- **Unidentified lines**
- **Insufficient auxiliary handles**

Result needs confirmation or repudiation

An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{M t_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)
Large Q value, fast $\beta\beta(0\nu)$
Good source radiopurity
Demonstrated technology
Ease of operation
Natural isotope
Small volume, source = detector
Good energy resolution
Slow $\beta\beta(2\nu)$ rate
Identify daughter in real time
Event reconstruction
Nuclear theory

Signal:Background ~ 1:1
Its all about the background

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
$5x10^{26}$	10	100	
$5x10^{27}$	**To reach atmospheric scale need BG on order 1/t-y.**	40	Atmospheric
$>10^{29}$	<0.05	<10	Solar

Previous Background Levels

Experiment	Background (cnts/ ROI-t-y)	Width (1 FWHM)
IGEX	960 (400 with PSD)	4 keV ROI
Heid-Moscow	440 (50 with PSD)	4 keV ROI
CUORICINO	1440	8 keV ROI
GERDA	81 (no PSD)	4 keV ROI
EXO-200	130	106 keV ROI (1.8% 1 sig resol.)
KamLAND-Zen	~55(~2400per t(Xe))	Width not explicitly given

Background is per tonne of material – big difference for KamLAND-Zen

Background Considerations

At atmospheric scale, expect a signal rate on the order of 1 count/tonne-year

- $\beta\beta(2\nu)$
- **natural occurring radioactive materials**
- **neutrons**
- **long-lived cosmogenics**

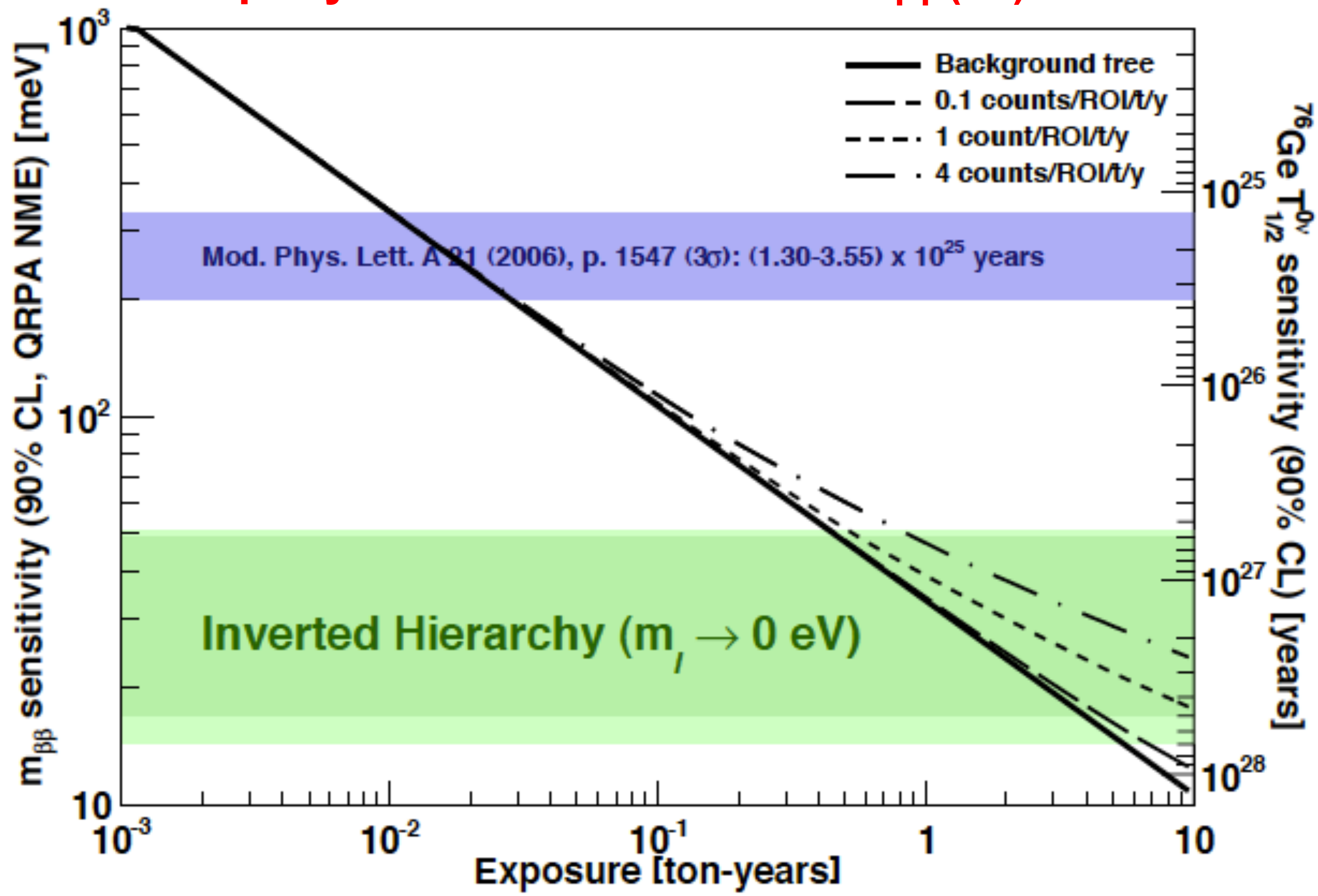
Great Number of Proposed Experiments

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
LUCIFER	^{82}Se	18 kg	ZnSe scintillating bolometers	Development	Gran Sasso
DCBA	[illegible]	20 kg	Nd foils and tracking	Development	Kamioka
SNO+[9]	^{150}Nd	43.7 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
Quantum Dots[8]	Various		Quantum Dots with isotope in liq. Scint.	Development	

- **Calorimeter**
  - Semi-conductors
  - Bolometers
  - Crystals/nanoparticles immersed in scintillator
- **Tracking**
  - Liquid or gas TPCs
  - Thin source with wire chamber or scintillator

Sensitivity, Background and Exposure

Goal is to achieve ultra-low backgrounds of less than 1 count per ton of material per year in the ROI about the $\beta\beta(0\nu)$ Q-value energy.



The MAJORANA Collaboration

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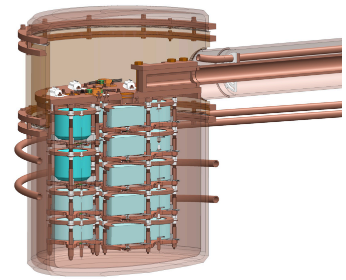
MAJORANA DEMONSTRATOR R&D Goals

- **Technical goals:**
  - **Demonstrate backgrounds low enough to justify building a tonne scale Ge experiment.**
  - **Establish feasibility to construct & field modular arrays of Ge detectors.**
  - **Minimize costs, optimize the schedule, and retire risks for a future 1-tonne experiment.**
- **Science goals:**
  - **Although we are driven by technical goals, we also aim to extract the maximum science from the DEMONSTRATOR prototype,**
    - **Test the recent claim of an observation of $0\nu\beta\beta$ in ^{76}Ge.**
    - **Exploit the low-energy sensitivity to perform searches for dark matter, axions.**
- **Work cooperatively with GERDA Collaboration toward a single international tonne-scale Ge experiment that combines the best features of MAJORANA and GERDA.**

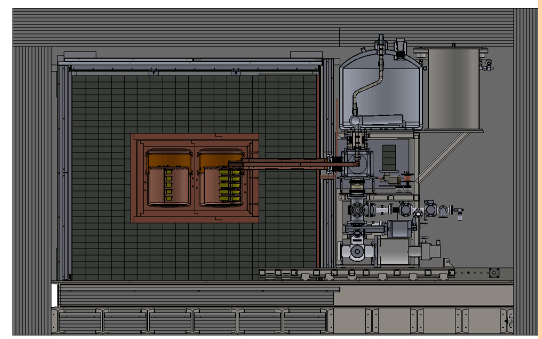
The MAJORANA DEMONSTRATOR Module

^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- **40-kg of Ge detectors**
  - **30-kg of 86% enriched ^{76}Ge crystals required for science and background goals**
  - **Point-contact detectors for DEMONSTRATOR**
- **Low-background Cryostats & Shield**
  - **ultra-clean, electroformed Cu**
  - **naturally scalable**
  - **Compact low-background passive Cu and Pb shield with active muon veto**

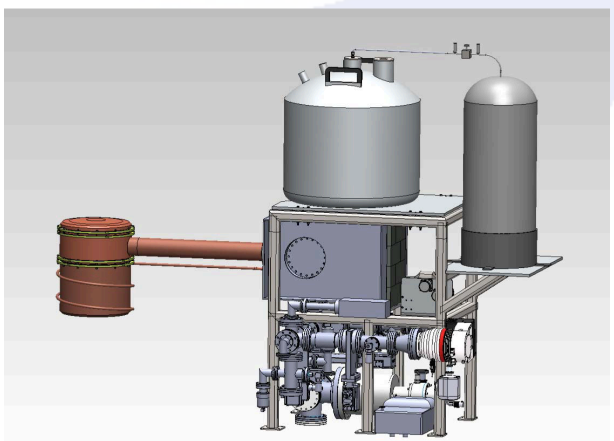


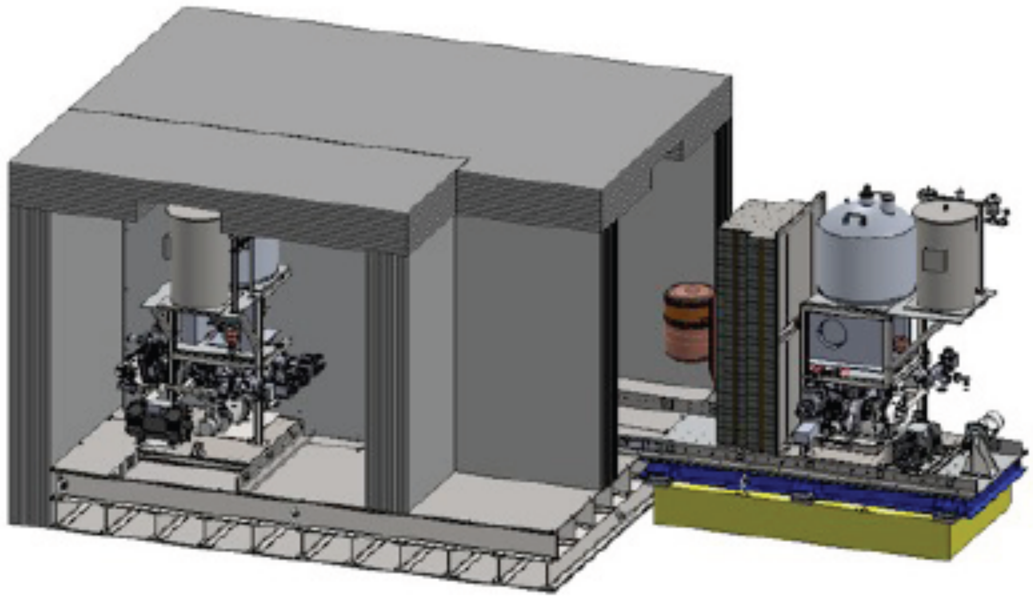
- **Located at 4850' level at Sanford Lab**
- **Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)**

~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

MJD Implementation

- **Three Phases**
  - **Prototype cryostat (2 strings, ^{nat}Ge)** **(Spring 2013)**
  - **Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge)** **(Late 2013)**
  - **Cryostat 2 (up to 7 strings ^{enr}Ge)** **(Fall 2014)**



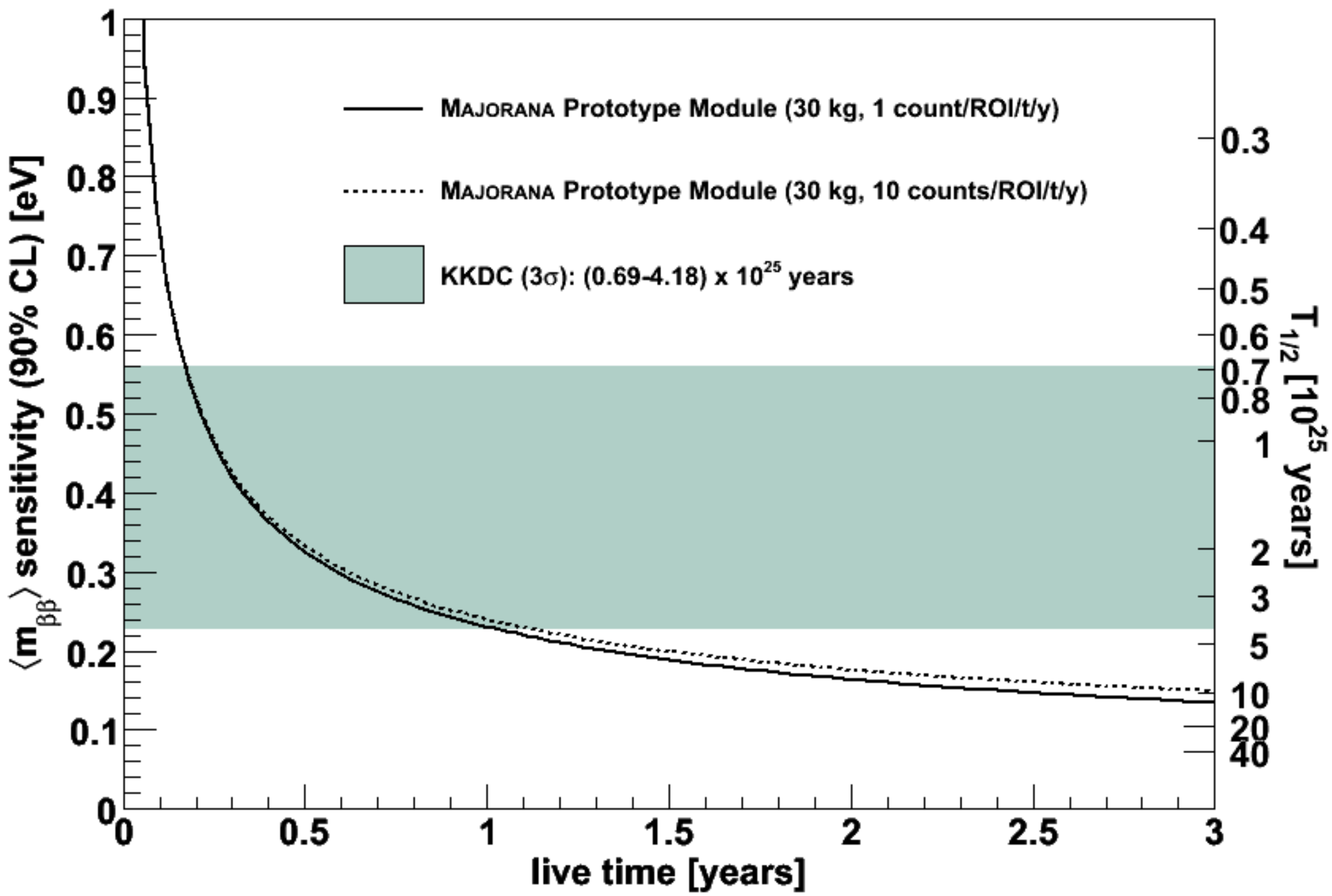


MAJORANA DEMONSTRATOR Module Sensitivity

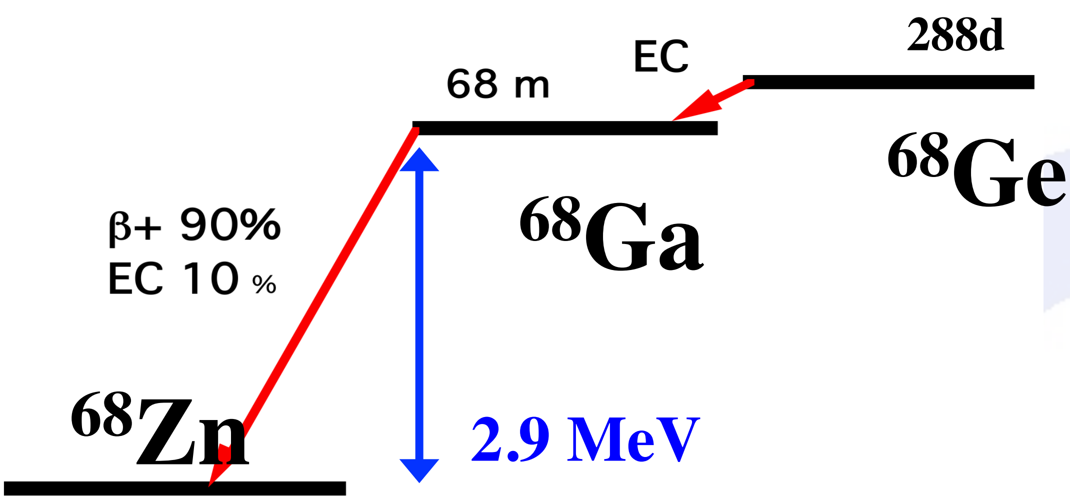
- **Expected Sensitivity to 0νββ**

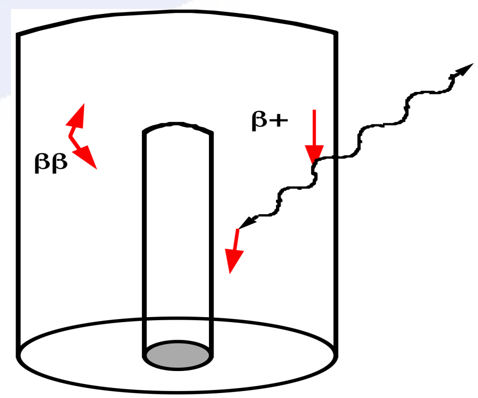
(30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

$T_{1/2} \geq 10^{26}$ y (90% CL).Sensitivity to $<m_\nu>$ < 140 meV (90% CL) [Rod05,err.]



Cosmogenic ^{68}Ge and ^{60}Co





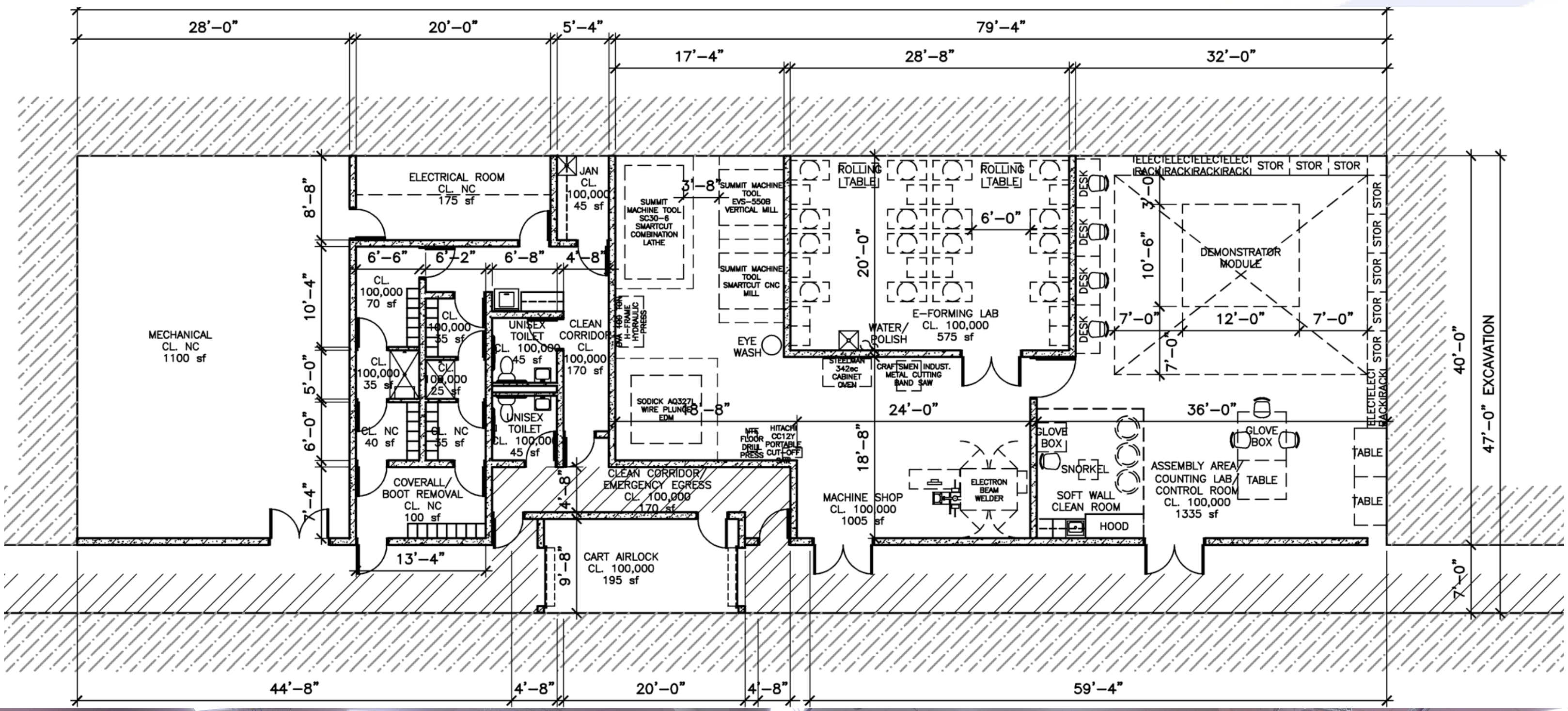
^{68}Ge and ^{60}Co are the dangerous internal backgrounds

For 60-kg enriched detector, initially
expect ~60 ^{68}Ge decays/day. $\tau_{1\backslash 2}$ = 288 d

Minimize exposure on surface during enrichment and fabrication

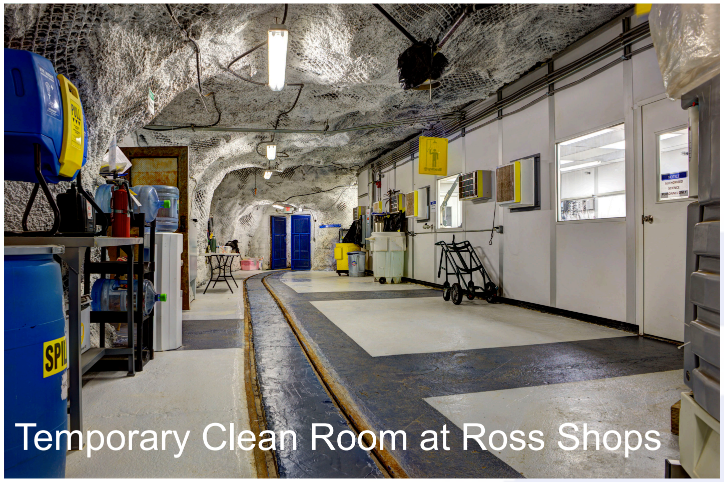
PSD, segmentation, time correlation cuts are effective at reducing these

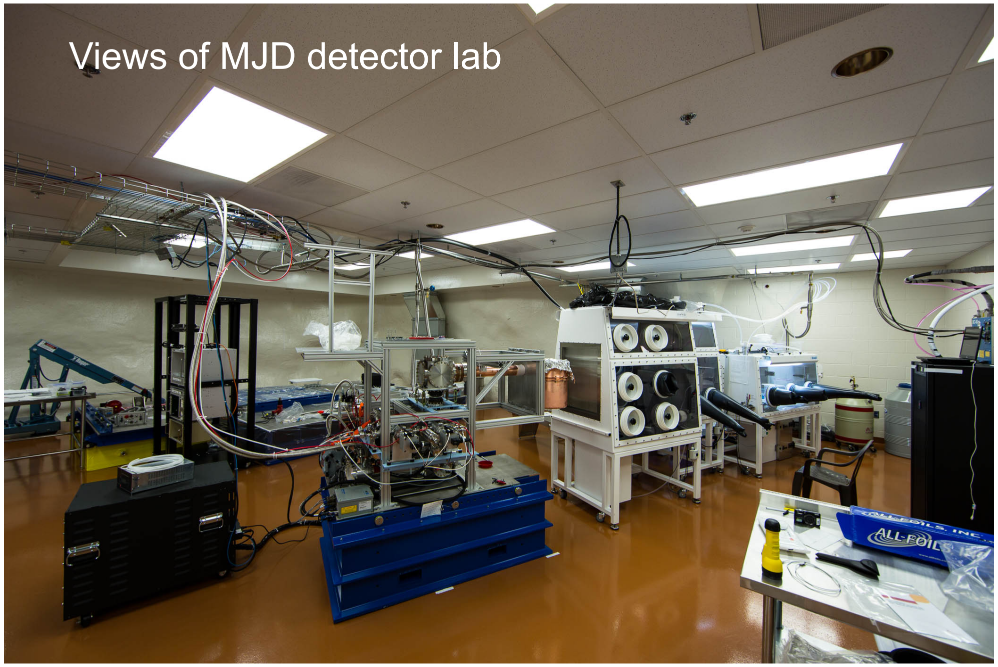
Underground Laboratory



Underground Lab - Status

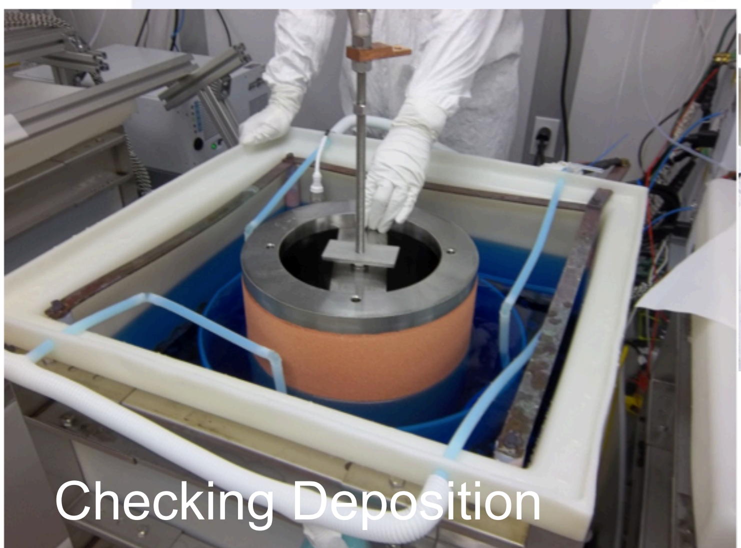
- Eforming lab operational since summer 2011
- Davis Campus lab outfitting finished
- Shield floor, LN system, assembly table, air bearing system, glove boxes, localized clean space all installed


Temporary Clean Room at Ross Shops


Views of MJD detector lab

Electroforming

- Eforming at PNNL and at 4850’ at SURF
- Machine shop operational



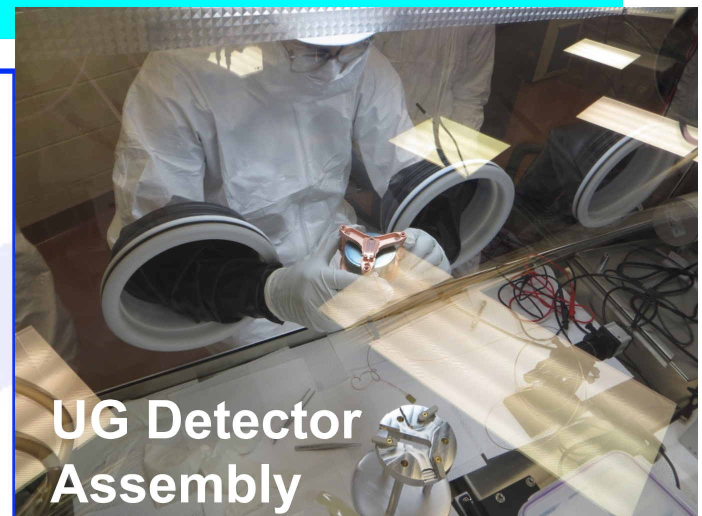
Enriched Ge

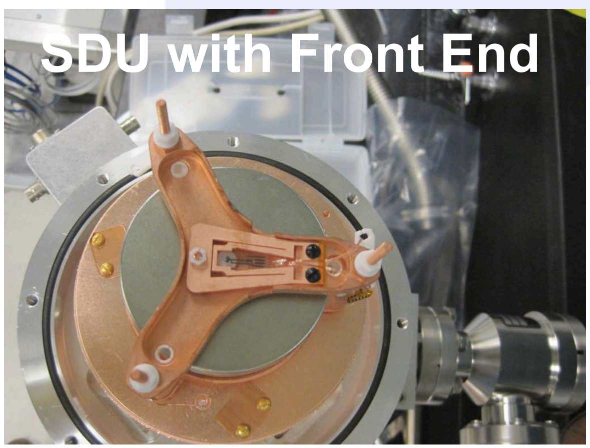
- 42.5 kg ^{enr}Ge received as oxide and stored UG in Oak Ridge
- 4-5 kg Russian contribution

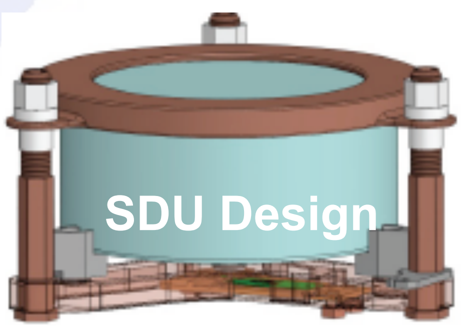
	Specs	ECP	ORNL Physics (Sample 1)	ORNL CSD (sample 2)	PNNL (Sample 3)
^{76}Ge	≥86.0	87.67	86.9 (2)	87.9 (9)	88.2 (3)
^{74}Ge		12.16	12.5 (1)	12.0 (1)	11.8 (3)
^{73}Ge		0.07	< 0.2	0.052 (1)	0.04 (2)
^{72}Ge		0.05	<0.2	0.0058 (3)	0.02 (1)
^{70}Ge	≤0.07	0.05	<0.2	0.0157 (3)	0.005 (4)

Detectors

- 20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 dets. UG).
- ORTEC selected to produce enriched detectors. Excellent projected yield.
- First enriched detectors (5) delivered UG in February 2013.







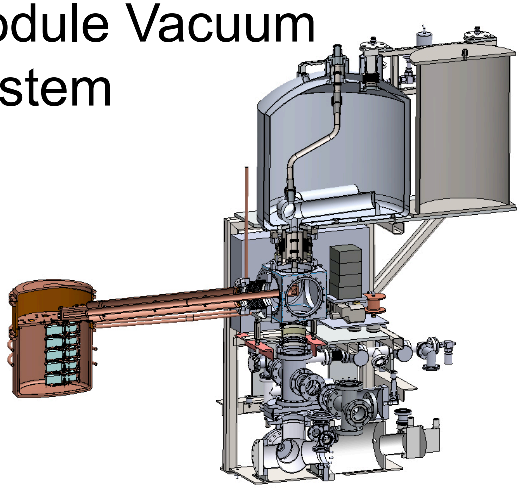
Modules

Thermosyphon System Parts

- **Prototype cryostat being fabricated and assembled. E-beam welds completed**
- **Thermosyphon design validated. Fabricated and tested.**
- **Prototype vacuum system designed, reviewed, assembled, and being operated.**
- **String test cryostats built.**
- **Parts and material tracking in place.**
- **Clean machining implemented underground.**

Cryostat hoop weld test

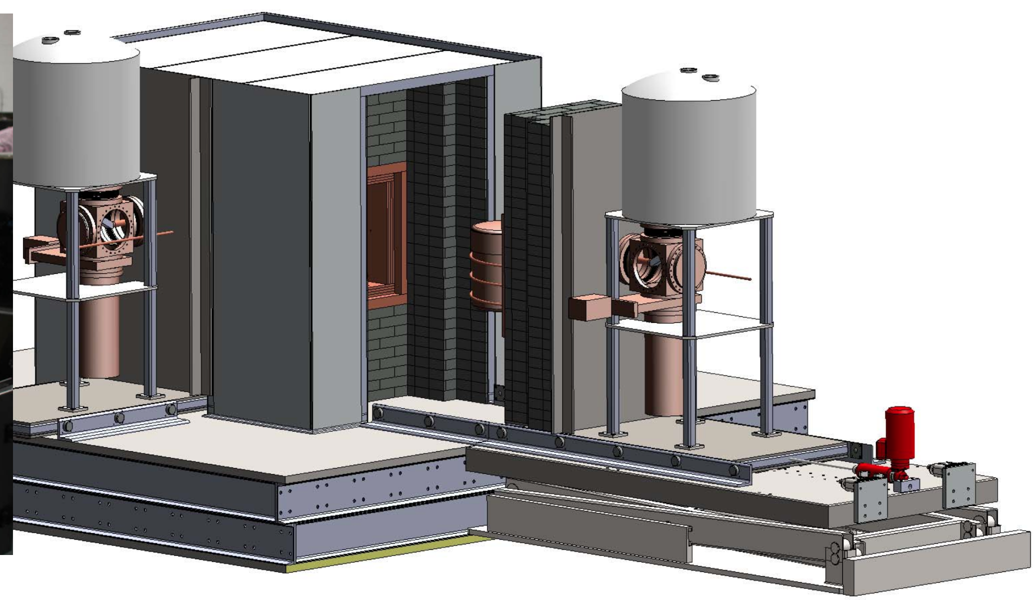
Module Vacuum System



Prototype Module Vacuum System

Mechanical Systems

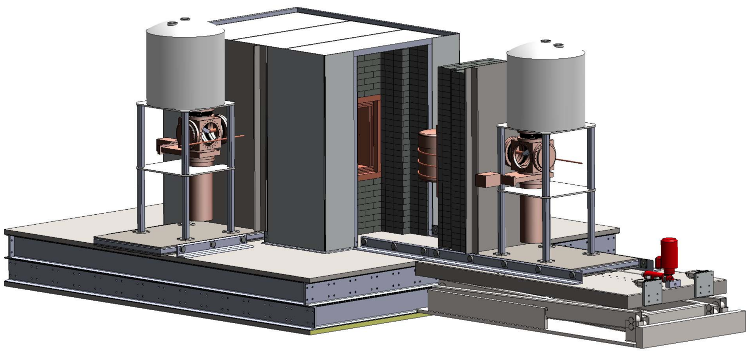
- Glove box (Mbraun) underground.
- Hovair delivered and tested.
- Overfloor installed UG.
- Majority of shielding material in hand, some is underground.
- Prototype calibration system demonstrated.

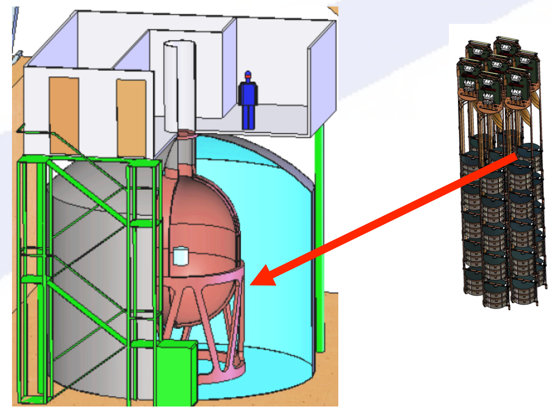


Towards 1TGe

MAJORANA

GERDA





- **Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat**
- **Shield: electroformed copper / lead**
- **Initial phase: R&D demonstrator module: Total ~40 kg (up to 30 kg enr.)**

- **'Bare' ^{enr}Ge array in liquid argon**
- **Shield: high-purity liquid Argon / H_2O**
- **Phase I (2012): ~18 kg (HdM/IGEX diodes)**
- **Phase II (2013): add ~20 kg new detectors - Total ~40 kg**

Joint Cooperative Agreement:

- **Open exchange of knowledge & technologies (e.g. MaGe, R&D)**
- **Intention is to merge for tonne-scale experiment. Select best techniques developed and tested in GERDA and MAJORANA**

MJD Overview

- Assembly and construction proceeding at Sanford Davis Campus laboratory.
- Based on assays, material backgrounds projected to meet cleanliness goals.
- EF copper being produced underground at SURF and PNNL
- Successful reduction and refinement of first 20 kg of ^{enr}Ge with 97.3% yield. Second batch purification underway.
- Detector vendor AMTEK (ORTEC) has produced detectors from the reduced/refined ^{enr}Ge. 5 underground at SURF.

Schedule
– Prototype Cryostat – Spring 2013
– Cryostat 1 – Late 2013
– Cryostat 2 - Fall 2014